

Elemental Abundances in PG1159 Stars

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Abstract. The hydrogen-deficiency in extremely hot post-AGB stars of spectral class PG1159 is probably caused by a (very) late helium-shell flash or a AGB final thermal pulse that consumes the hydrogen envelope, exposing the usually-hidden intershell region. Thus, the photospheric elemental abundances of these stars allow to draw conclusions about details of nuclear burning and mixing processes in the precursor AGB stars. We compare predicted elemental abundances to those determined by quantitative spectral analyses performed with advanced non-LTE model atmospheres. A good qualitative and quantitative agreement is found for many species (He, C, N, O, Ne, F, Si, Ar) but discrepancies for others (P, S, Fe) point at shortcomings in stellar evolution models for AGB stars. PG1159 stars appear to be the direct progeny of [WC] stars.

1. Main characteristics of PG1159 stars

The PG1159 stars are a group of 40 extremely hot hydrogen-deficient post-AGB stars. Their effective temperatures (T_{eff}) range between 75 000 and 200 000 K. Many of them are still heating up along the constant-luminosity part of their post-AGB evolutionary path in the HR diagram ($L \approx 10^4 L_{\odot}$) but most of them are already fading along the hot end of the white dwarf cooling sequence (with $L \gtrsim 10 L_{\odot}$). Luminosities and masses are inferred from spectroscopically determined T_{eff} and surface gravity ($\log g$) by comparison with theoretical evolutionary tracks. The position of analysed PG1159 stars in the “observational HR diagram”, i.e., the $T_{\text{eff}}-g$ diagram, are displayed in Fig. 1. The high-luminosity stars have low $\log g$ (≈ 5.5) while the low-luminosity stars have a high surface gravity (≈ 7.5) that is typical for white dwarf (WD) stars. The derived mean mass is $0.57 M_{\odot}$, a value that is practically identical to the mean mass of WDs (Bergeron et al. 2007). The PG1159 stars co-exist with hot central stars of planetary nebulae and the hottest hydrogen-rich (DA) white dwarfs in the same region of the HR diagram. About every other PG1159 star is surrounded by an old, extended planetary nebula. For a recent review with a detailed bibliography see Werner & Herwig (2006).

What is the characteristic feature that discerns PG1159 stars from “usual” hot central stars and hot WDs? Spectroscopically, it is the lack of hydrogen Balmer lines, pointing at a H-deficient surface chemistry. The proof of H-deficiency, however, is not easy: The stars are very hot, H is strongly ionized

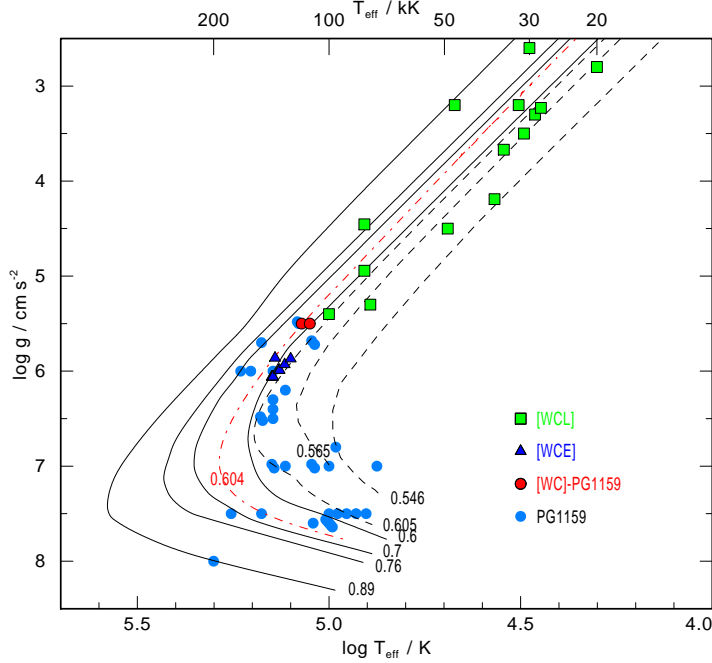


Figure 1. Hot hydrogen-deficient post-AGB stars in the g - T_{eff} -plane. We identify Wolf-Rayet central stars of early and late type ([WCE], [WCL], from Hamann 1997), PG1159 stars (from Werner & Herwig 2006) as well as two [WC]-PG1159 transition objects (Abell 30 and 78). Evolutionary tracks are from Schönberner (1983) and Blöcker (1995) (dashed lines), Wood & Faulkner (1986) and Herwig (2003) (dot-dashed line; labels: mass in M_{\odot}). The latter $0.604 M_{\odot}$ track is the final CSPN track following a VLTP evolution and therefore has a H-deficient composition. However, the difference between the tracks is mainly due to the different AGB progenitor evolution.

and the lack of Balmer lines could simply be an ionisation effect. In addition, every Balmer line is blended by a Pickering line of ionized helium. Hence, only detailed modeling of the spectra can give reliable results on the photospheric composition. The high effective temperatures require non-LTE modeling of the atmospheres. Such models for H-deficient compositions have only become available in the early 1990s after new numerical techniques have been developed and computers became capable enough.

The first quantitative spectral analyses of optical spectra from PG1159 stars indeed confirmed their H-deficient nature (Werner et al. 1991). It could be shown that the main atmospheric constituents are C, He, and O. The typical abundance pattern is C=0.50, He=0.35, O=0.15 (mass fractions). It was speculated that these stars exhibit intershell matter on their surface, however, the C and O abundances were much higher than predicted from stellar evolution models. It was further speculated that the H-deficiency is caused by a late He-shell flash, suffered by the star during post-AGB evolution, laying bare the intershell layers. The re-ignition of He-shell burning brings the star back onto the AGB, giving rise to the designation “born-again” AGB star (Iben et al. 1983). If this scenario is true, then the intershell abundances in the models have to

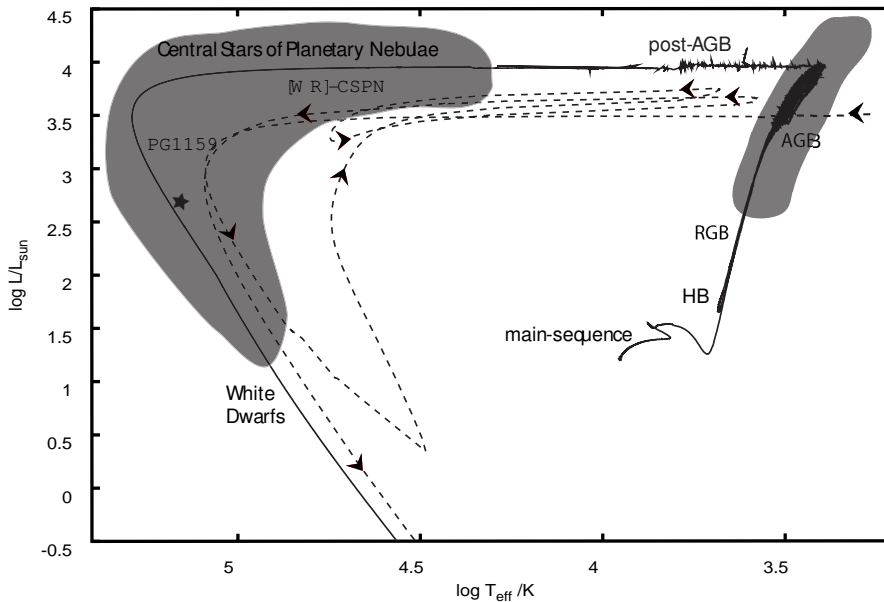


Figure 2. Complete stellar evolution track with an initial mass of $2M_{\odot}$ from the main sequence through the RGB phase, the HB to the AGB phase, and finally through the post-AGB phase that includes the central stars of planetary nebulae to the final WD stage. The solid line represents the evolution of a H-normal post-AGB star. The dashed line shows a born-again evolution of the same mass, triggered by a very late thermal pulse, however, shifted by approximately $\Delta \log T_{\text{eff}} = -0.2$ and $\Delta \log L/L_{\odot} = -0.5$ for clarity. The double-loop structure of the path is the consequence of a hydrogen-ingestion flash. The “★” symbol shows the position of PG1159–035 (from Werner & Herwig 2006).

be brought into agreement with observations. By introducing a more effective overshoot prescription for the He-shell flash convection during thermal pulses on the AGB, dredge-up of carbon and oxygen into the intershell can achieve this agreement (Herwig et al. 1999). Another strong support for the born-again scenario was the detection of neon lines in optical spectra of some PG1159 stars (Werner & Rauch 1994). The abundance analysis revealed $\text{Ne}=0.02$, which is in good agreement with the Ne intershell abundance in the improved stellar models.

If we do accept the hypothesis that PG1159 stars display former intershell matter on their surface, then we can in turn use these stars as a tool to investigate intershell abundances of other elements. Therefore these stars offer the unique possibility to directly see the outcome of nuclear reactions and mixing processes in the intershell of AGB stars. Usually the intershell is kept hidden below a thick H-rich stellar mantle and the only chance to obtain information about intershell processes is the occurrence of the third dredge-up. This indirect view onto intershell abundances makes the interpretation of the nuclear and mixing processes very difficult, because the abundances of the dredged-up elements may have been changed by additional burning and mixing processes in the H-envelope

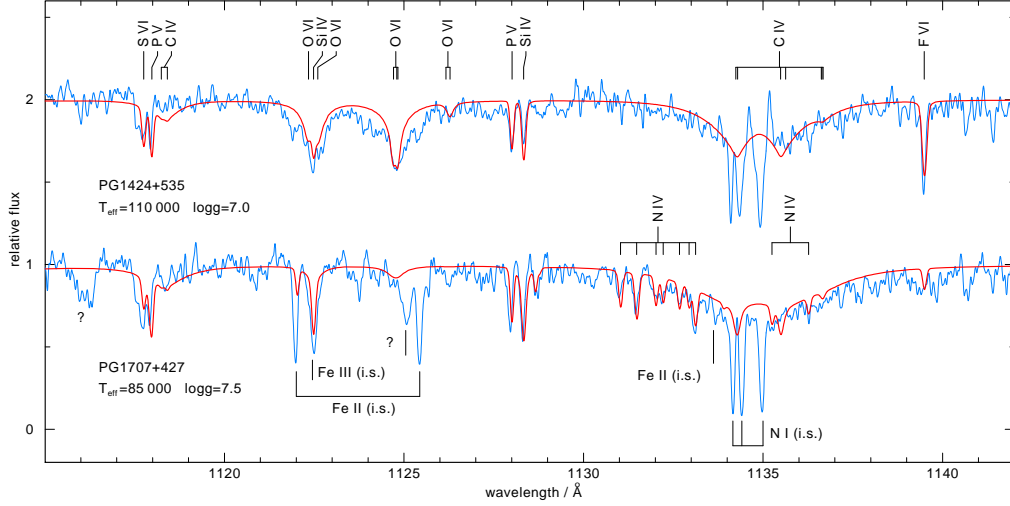


Figure 3. Detail from FUSE spectra of two relatively cool PG1159 stars (see labels). Note the following features. The F VI 1139.5 Å line which is the first detection of fluorine at all in a hot post-AGB star; the P V resonance doublet at 1118.0 and 1128.0 Å, the first discovery of phosphorus in PG1159 stars; the N IV multiplet at 1132 Å. Also detected are lines from Si IV and S VI. The broader features stem from C IV and O VI (Reiff et al. 2007).

(e.g., hot-bottom burning). In addition, stars with an initial mass below $1.5 M_{\odot}$ do not experience a third dredge-up at all.

The central stars of planetary nebulae of spectral type [WC] are believed to be immediate progenitors of PG1159 stars, representing the evolutionary phase between the early post-AGB and PG1159 stages. This is based on spectral analyses of [WC] stars which yield very similar abundance results (see papers by Crowther, Todt, and Gräfenr in these proceedings).

2. Mass determination: spectroscopy and asteroseismology

As mentioned, the mean spectroscopic mass of PG1159 stars is $0.57 M_{\odot}$. This result was derived from the spectroscopic temperature and gravity determination and comparison with modern evolutionary tracks for H-deficient post-AGB stars (Miller Bertolami & Althaus 2006). This is a systematic shift towards a lower mean mass compared to our previously determined value ($0.62 M_{\odot}$) that was derived from H-rich surface tracks (Werner & Herwig 2006).

Some PG1159 stars are multi-periodic non-radial g-mode pulsators, defining the group of GW Vir stars (see, e.g., Quirion et al. in these proceedings). Stellar masses from asteroseismic modeling were derived for five objects and we compare the results to the spectroscopic masses in Table 1. Considering the uncertainties of both methods we can claim consistent results, except for RX J2117.1+3412.

The result of an asteroseismic mass determination depends upon the analysis method used. Althaus et al. (2007) discuss in detail the results derived from three methods, namely, the asymptotic and the average period spacings, and detailed period fitting. The spectroscopic mass determination is most strongly

Table 1. Spectroscopic vs. asteroseismic masses. The spectroscopic masses of RX J2117.1+3412 and the other four objects are based on the temperature and gravity determinations by Werner et al. (1996) and Dreizler & Heber (1998), respectively, and on the H-deficient evolutionary tracks of Miller Bertolami & Althaus (2006). The asteroseismic masses are from Althaus et al. (2007). The given ranges result from different pulsational analysis methods.

Star	$M_{\text{spec}}/M_{\odot}$	$M_{\text{puls}}/M_{\odot}$
PG 2131+066	0.55	0.58–0.63
PG 0122+200	0.53	0.56–0.62
RX J2117.1+3412	0.72	0.56–0.57
PG 1159–035	0.54	0.56–0.58
PG 1707+427	0.53	0.57–0.60

affected by the uncertainty in gravity. The accuracy is ≈ 0.3 – 0.5 dex, which propagates to an error of the order 0.05 – $0.1 M_{\odot}$, depending on the star’s location in the g – T_{eff} -plane. It is therefore fair to say that in the current state the asteroseismology and spectroscopy results are of comparable accuracy.

Why should we care that the mass of a PG1159 star is uncertain by $0.1 M_{\odot}$? The answer is, that the predicted intershell abundances strongly depend on the post-AGB remnant mass. That is because the uncertainty in the respective main sequence progenitor mass becomes large. According to the initial-final mass relation (Weidemann 2000), 0.60 and $0.68 M_{\odot}$ remnants have evolved from 2.0 and $3.0 M_{\odot}$ main sequence stars, respectively. E.g., depending on metallicity, the predicted intershell fluorine abundance in these stars can differ by an order of magnitude (Lugaro et al. 2004). Therefore, if we want to use abundance patterns of PG1159 stars as a tool to investigate AGB star nucleosynthesis, then we need a good mass determination. In turn, if one believes that AGB star models describe nucleosynthesis precisely enough, then the observed abundance pattern of a PG1159 star can independently constrain its mass.

The recent discovery of a PG1159 star in a close binary system (Nagel et al. (2006), and Schuh et al. in these proceedings) might lead to a dynamical mass determination, being an independent check for the spectroscopic mass. Unfortunately, this star is a non-pulsator, preventing an asteroseismic investigation.

3. Three different late He-shell flash scenarios

The course of events after the final He-shell flash is qualitatively different depending on the moment when the flash starts. We speak about a very late thermal pulse (VLTP) when it occurs in a WD, i.e., the star had turned around the “knee” in the HR diagram and H-shell burning has already stopped (Fig. 2). The star expands and develops a H-envelope convection zone that eventually reaches deep enough that H-burning sets in (a so-called hydrogen-ingestion flash). Hence H is destroyed and whatever H abundance remains, it will probably be shed off from the star during the “born-again” AGB phase. A late thermal pulse (LTP) denotes the occurrence of the final flash in a post-AGB star that is still burning hydrogen, i.e., it is on the horizontal part of the post-AGB track, before the

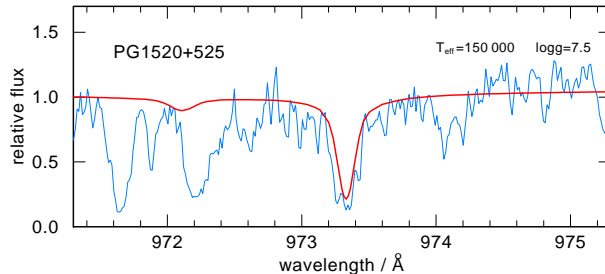


Figure 4. First identification of the Ne VII 973.3 Å line, shown here in the FUSE spectrum of the PG1159 star PG1520+525. This strong absorption feature is seen in the spectra many hot post-AGB stars, but remained unidentified for some years (Werner et al. 2004a).

“knee”. In contrast to the VLTP case, the bottom of the developing H-envelope convection zone does not reach deep enough layers to burn H. The H-envelope (having a mass of about $10^{-4} M_{\odot}$) is mixed with a few times $10^{-3} M_{\odot}$ intershell material, leading to a dilution of H down to about $H=0.02$, which is below the spectroscopic detection limit. If the final flash occurs immediately before the star departs from the AGB, then we talk about an AFTP (AGB final thermal pulse). In contrast to an ordinary AGB thermal pulse the H-envelope mass is particularly small. Like in the LTP case, H is just diluted with intershell material and not burned. The remaining H abundance is relatively high, well above the detection limit ($H \gtrsim 0.1$).

There are three objects, from which we believe to have witnessed a (very) late thermal pulse during the last ≈ 100 years (details on these stars are presented in several other papers of these proceedings). FG Sge suffered a late flash in 1894 (Gonzalez et al. 1998). The star became rich in C and rare earth elements. It most probably was hit by an LTP, not a VLTP, because it turned H-deficient only recently (if at all, this is still under debate). As of today, FG Sge is located on or close to the AGB. V605 Aql has experienced a VLTP in 1917 (Clayton & De Marco 1997). Since then, it has quickly evolved back towards the AGB, began to reheat and is now in its second post-AGB phase. It has now an effective temperature of the order 100 000 K and is H-deficient. Sakurai’s object (V4334 Sgr) also experienced a VLTP, starting around 1993 (Duerbeck & Benetti 1996). It quickly evolved back to the AGB and became H-deficient. Recent observations indicate that the reheating of the star has already begun, i.e., its second departure from the AGB may be in progress.

The spectroscopic study of FG Sge and Sakurai’s object is particularly interesting, because we can observe how the surface abundances change with time. The stars are still cool, so that isotopic ratios can be studied from molecule lines, and abundances of many metals can be determined. The situation is less favorable with the hot PG1159 stars: All elements are highly ionised and for many of them no atomic data are available for quantitative analyses. On the other hand, in the cool born-again stars the He-intershell material is once again partially concealed.

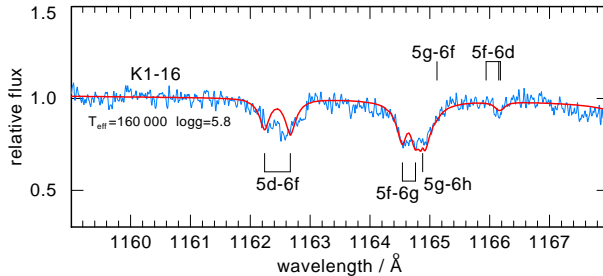


Figure 5. Discovery of Ne VIII lines in the FUSE spectrum of the PG1159-type central star of K1-16. This is the first detection of Ne VIII in any photospheric spectrum (Werner et al. 2007b). Lines from this ion are only exhibited by the very hottest post-AGB stars ($T_{\text{eff}} \geq 140\,000$ K).

4. Comparison of observed and predicted elemental abundances

Abundance analyses of PG1159 stars are performed by detailed fits to spectral line profiles. Because of the high T_{eff} all species are highly ionized and, hence, most metals are only accessible by UV spectroscopy. Optical spectra always exhibit lines from He II and C IV. Only the hottest PG1159 stars display additional lines of N, O, and Ne (N V, O VI, Ne VII). For all other species we have utilized high-resolution UV spectra that were taken with the *Hubble Space Telescope* (HST) and the *Far Ultraviolet Spectroscopic Explorer* (FUSE). FUSE allowed observations in the Lyman-UV range ($\approx 900\text{--}1200$ Å) that is not accessible with HST. This turned out to be essential for most results reported here.

A number of chemical elements could be identified for the very first time (F, P, S, Ar). In addition, very high ionisation stages of several elements, which were never seen before in stellar photospheric spectra, could be identified in the UV spectra for the very first time (e.g. Si V, Si VI, Ne VIII). To illustrate this, we display in Figs. 3–8 details of FUSE and HST spectra of PG1159 stars. We discuss the spectroscopic results comparing with [WC]s and model predictions.

Hydrogen – Four PG1159 stars show residual H with an abundance of 0.17 (so-called hybrid-PG1159 stars). These objects are the outcome of an AFTP. All other PG1159 stars have $H \lesssim 0.1$ and, hence, should be LTP or VLTP objects. H was also found in [WCL] stars ($H=0.01\text{--}0.1$).

Helium, carbon, oxygen – These are the main constituents of PG1159 atmospheres. A large variety of relative He/C/O abundances is observed. The approximate abundance ranges are: He=0.30–0.85, C=0.13–0.60, O=0.02–0.20. The spread of abundances might be explained by different numbers of thermal pulses during the AGB phase, except for the most He-rich stars. They might belong to a different post-AGB sequence involving the so-called O(He) stars (see Rauch et al. in these proceedings). The He/C/O abundances in PG1159 stars are consistent with results found for [WC] stars.

Nitrogen – N is a key element that allows to decide if the star is the product of a VLTP or a LTP. Models predict that N is diluted during an LTP so that in the end $N=0.1\%$. This low N abundance is undetectable in the optical and only detectable in extremely good UV spectra. In contrast, a VLTP produces N (because of H-ingestion and burning) to an amount of 1% to maybe a few

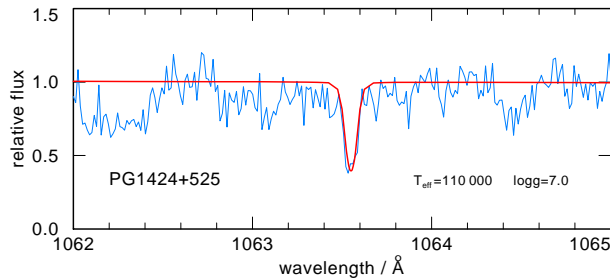


Figure 6. Discovery of the Ar VII 1063.55 Å line in the FUSE spectrum of the PG1159 star PG1425+535. This is the first detection of Ar VII in a photospheric spectrum and the only detectable argon line in any wavelength region of hot post-AGB stars (Werner et al. 2007a).

percent. N abundances of the order 1% are found in some PG1159 stars, while in others it is definitely much lower. This picture is similar to the [WC] stars.

Neon – Ne is made from ^{14}N that was produced by CNO burning. In the He-burning region, α -captures transform ^{14}N to ^{22}Ne . Evolution models predict $\text{Ne}=0.02$ in the intershell. A small spread is expected as a consequence of different initial stellar masses. $\text{Ne}=0.02$ was first found from optical analyses of a few stars and, later, in a larger sample observed with FUSE (Werner et al. 2004a). The Ne abundance in [WC] stars is very similar (0.02–0.04).

Fluorine – F was for the first time discovered by Werner et al. (2005) in hot post-AGB stars; in PG1159 stars as well as hydrogen-normal central stars. A strong absorption line in FUSE spectra located at 1139.5 Å remained unidentified until we found that it stems from F VI. The abundances derived for PG1159 stars show a large spread, ranging from solar to up to 250 times solar. This was surprising at the outset because ^{19}F , the only stable F isotope, is very fragile and easily destroyed by H and He. A comparison with AGB star models of Lugaro et al. (2004), however, shows that such high F abundances in the intershell can indeed be accumulated by the reaction $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\text{p}, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$, the amount depends on the stellar mass. We find a good agreement between observation and theory. Our results also suggest, however, that the F overabundances found in AGB stars (Jorissen et al. 1992) can only be understood if the dredge-up in AGB stars is much more efficient than hitherto thought.

Silicon – Si is expected to remain almost unchanged, in agreement with PG1159 stars for which we could determine the Si abundance. The same holds for some [WC] stars, but in other cases overabundances were found (8–45 times solar).

Phosphorus – Systematic predictions from evolutionary model grids are not available; however, the few computed models show P overabundances in the range 4–25 times solar (Lugaro priv. comm.). This is at odds with our spectroscopic measurements for two PG1159 stars, that reveal a solar P abundance.

Sulfur – Again, model predictions are uncertain at the moment. Current models show a slight (0.6 solar) underabundance. In strong contrast, we find a large spread of S abundances in PG1159 stars, ranging from solar down to 0.01 solar.

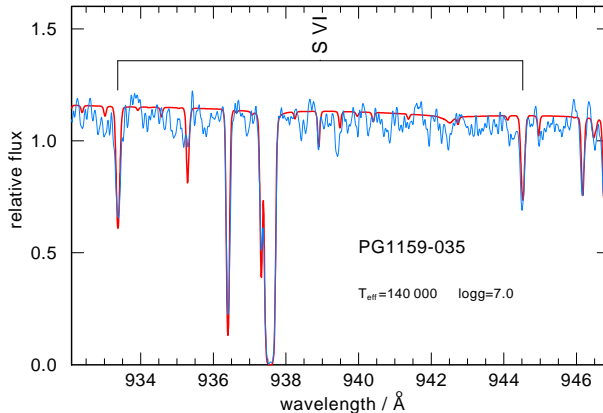


Figure 7. FUSE enabled the first abundance determination of sulfur in PG1159 stars. Shown here is the S VI resonance doublet in the prototype of the PG1159 spectral class, PG1159–035 (Jahn et al. 2007).

Argon – Ar was identified recently for the first time in hot post-AGB stars and white dwarfs (Werner et al. 2007a). Among them is one PG1159 star for which a solar abundance has been determined (Fig. 6). This is in agreement with AGB star models which predict that the Ar abundance remains almost unchanged.

Iron and Nickel – Fe VII lines are expected to be the strongest iron features in PG1159 stars. They are located in the UV range. One of the most surprising results is the non-detection of these lines in three examined PG1159 stars (K1-16, NGC 7094, PG1159–035; see, e.g., Fig. 9). The derived upper abundance limits (e.g. Werner et al. 2003; Jahn et al. 2007) indicate that iron is depleted by about 0.7–2 dex, depending on the particular object. Iron depletions were also found for the PG1159-[WC] transition object Abell 78 as well as for several PG1159 progenitors, the [WC] stars. It must be stressed that in no single case a solar (or almost solar) Fe abundance was found. Such high Fe depletions are not in agreement with current AGB models. Destruction of ^{56}Fe by neutron captures is taking place in the AGB star intershell as a starting point of the s-process; however, the resulting depletion of Fe in the intershell is predicted to be small (about 0.2 dex). It could be that additional Fe depletion can occur during the late thermal pulse. In any case, we would expect a simultaneous enrichment of nickel, but up to now we were unable to detect Ni in PG1159 stars at all (see Reiff et al. in these proceedings).

A particularly mysterious problem is the Fe-deficiency in the hybrid-PG1159 central star NGC 7094 (Ziegler et al., these proceedings). We recall that the hybrid-PG1159 stars are the outcome of an AFTP with residual hydrogen ($H=0.17$) from the envelope that was mixed with intershell matter. One would expect to see at least the iron that was contained in the convective H-envelope, hence $\text{Fe}/H \approx \text{solar}$. This is not the case: the upper limit for Fe/H ratio is much smaller.

Trans-iron elements – The discovery of s-process elements would be highly desirable. However, this is impossible due to the lack of atomic data. From the ionization potentials we expect that these elements are highly ionised like iron,

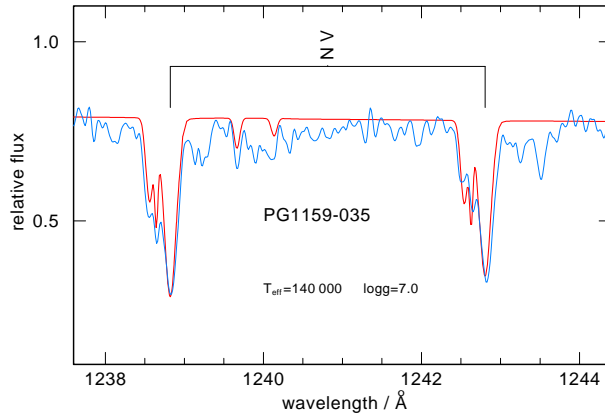


Figure 8. The high spectral resolution capability of STIS aboard HST allows to distinguish the photospheric N v resonance doublet from the weak blueshifted ISM components. This enabled the first reliable nitrogen abundance determination in the prototype PG1159–035 (Jahn et al. 2007).

i.e., the dominant ionization stages are VI – IX. To our best knowledge, there are no laboratory measurements of so highly ionised species that would allow us to search for atomic lines in the spectra. Such measurements would be crucial to continue the elemental abundance determination beyond the current state.

5. The enigmatic case of H1504+65

H1504+65 is the hottest PG1159 star ($T_{\text{eff}} = 200\,000$ K, $\log g = 8$), and it is H- and He-deficient (Werner et al. 2004b). The atmosphere is dominated by C and O (C=0.48, O=0.48, Ne=0.02, Mg=0.02). It is the most massive PG1159 star (0.74–0.97 M_{\odot}). However, its evolutionary history is completely unknown, and the model tracks used to derive the mass might be inappropriate. It was speculated that H1504+65 is a bare CO or even a ONeMg WD, so that the progenitor could have been a super-AGB star. In any case, the surface chemistry is a real challenge for evolution theory. Until now, H1504+65 appeared as a “singularity”, with no potential progenitor or progeny candidates. The recently discovered cool DQ WDs with almost pure C atmospheres, however, could represent such a progeny (Dufour et al., these proceedings).

6. Conclusions

It has been realized that PG1159 stars exhibit intershell matter on their surface, which has probably been laid bare by a late final thermal pulse. This provides the unique opportunity to study directly the result of nucleosynthesis and mixing processes in AGB stars. Abundance determinations in PG1159 stars are in agreement with intershell abundances predicted by AGB star models for many elements (He, C, N, O, Ne, F, Si, Ar). For other elements, however, disagreement is found (Fe, P, S) that points at possible weaknesses in the evolutionary models.

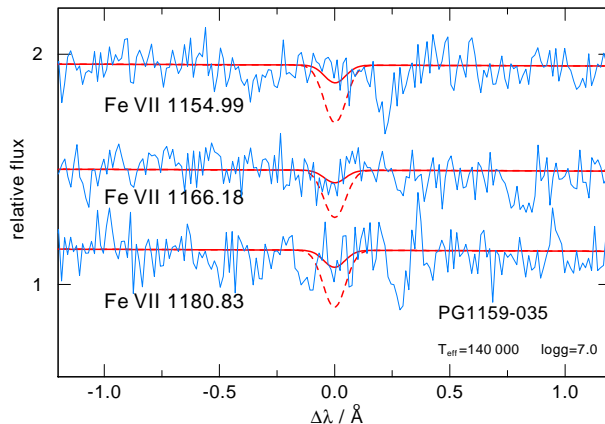


Figure 9. From the nondetection of Fe VII lines in PG1159–035 a Fe deficiency is found. Here we compare model spectra for three lines, each computed with solar and 0.1 solar Fe abundance, to the observation (Jahn et al. 2007).

Generally, the abundance patterns clearly support the idea that [WC] stars are direct progenitors of PG1159 stars.

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References

- Althaus, L. G., Córscico, A. H., Kepler, S. O., & Miller Bertolami, M. M. 2007, *A&A*, in press, arXiv:0710.3394v1 [astro-ph]
- Bergeron, P., Gianninas, A., & Boudreault, S. 2007, in *White Dwarfs*, eds. R. Napiwotzki, M.R. Burleigh, ASP Conference Series, 372, 29
- Blöcker, T. 1995, *A&A*, 299, 755
- Clayton, G. C., & De Marco, O. 1997, *AJ*, 114, 2679
- Dreizler, S., & Heber, U. 1998, *A&A*, 334, 618
- Duerbeck, H. W. & Benetti, S. 1996, *ApJ Lett.*, 468, L111
- Gonzalez, G., Lambert, D. L., Wallerstein, G., et al. 1998, *ApJS*, 114, 133
- Hamann, W.-R. 1997, *IAU Symp.* 180, 91
- Herwig, F. 2003, *IAU Symp.* 209, 111
- Herwig, F., Blöcker, T., Langer, N., & Driebe, T. 1999, *A&A*, 349, L5
- Iben, Jr., I., Kaler, J. B., Truran, J. W., & Renzini, A. 1983, *ApJ*, 264, 605
- Jahn, D., Rauch, T., Reiff, E., et al. 2007a, *A&A*, 462, 281
- Jorissen, A., Smith, V. V., & Lambert, D. L. 1992, *A&A*, 261, 164
- Lugaro, M., Ugalde, C., Karakas, A. I., et al. 2004, *ApJ*, 615, 934
- Miller Bertolami, M. M., & Althaus, L. G. 2006, *A&A*, 454, 845
- Nagel, T., Schuh, S., Kusterer, D.-J., et al. 2006, *A&A*, 448, L25
- Reiff, E., Rauch, T., Werner, K., Kruk, J. W., & Herwig, F. 2007, in *White Dwarfs*, eds. R. Napiwotzki, M.R. Burleigh, ASP Conference Series, 372, 237
- Schönberner, D. 1983, *ApJ*, 272, 708
- Weidemann, V. 2000, *A&A*, 363, 674
- Werner, K., & Rauch, T. 1994, *A&A*, 284, L5
- Werner, K., & Herwig, F. 2006, *PASP*, 118, 183

- Werner, K., Heber, U., & Hunger, K. 1991, A&A, 244, 437
Werner, K., Dreizler, S., Heber, U., et al. 1996, A&A, 307, 860
Werner, K., Deetjen, J. L., Dreizler, S., et al. 2003, IAU Symp. 209, 169
Werner, K., Rauch, T., Reiff, E., Kruk, J. W., & Napiwotzki, R. 2004a, A&A, 427, 685
Werner, K., Rauch, T., Barstow, M. A., & Kruk, J. W., 2004b, A&A, 421, 1169
Werner, K., Rauch, T., & Kruk, J. W. 2005, A&A, 433, 641
Werner, K., Rauch, T., & Kruk, J. W. 2007a, A&A, 466, 317
Werner, K., Rauch, T., & Kruk, J. W. 2007b, A&A, 474, 591
Wood, P. R., & Faulkner, D. J. 1986, ApJ, 307, 659